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Description

This invention relates to optical fibre with a fluorescent additive and in particular to fibre which is suitable for the construction of fibre lasers.

5 There is currently much technical interest in a wide range of devices in which radiation at wave lengths of 0.3 μm to 4 μm is generated in the core of an optical fibre. In these devices the fibre contains a fluorescent additive which interacts with excitation radiation, usually identified as the "pump radiation", to produce the desired output. The devices take many forms, e.g. broadband sources, super luminescent sources and temperature sensors, but devices which display laser activity are particularly important, especially in telecommunications. It should be realised that telecommunications uses laser activity in two
10 distinct manners namely optical oscillators and optical amplifiers. However the same doped glass fibres are equally suitable for a plurality of such applications (and often for all such applications).

Stone and Nurus in "Applied Physics Letters" (Volume 23, No. 7, 1 October 1973 at pages 388 and 389) disclose lasers made of neodymium doped silica with end-pumped fibre geometry. One of their
15 systems has an active core of fused SiO_2 and Nd_2O_3 enclosed in a thin passive sleeve of SiO_2 and Nb_2O_5 and enclosed in a fused jacket of SiO_2 . The diameter of the active core was about 800 to 150 μm and the length of the samples was 1cm. The function of the thin passive sleeve is to increase the guidance of the core and hence pump efficiency.

US Patent 3 808 549 describes an optical waveguide light source having an active core surrounded by an inner cladding layer and an outer cladding layer. The refractive index of the outer cladding is lower than
20 the refractive index of the inner cladding which is lower than the refractive index of the core. Pump radiation is launched into the inner cladding layer to which it is confined by the outer cladding. The pump radiation makes many passes through the core whereby its absorption by the core is increased. The signal is generated within the core.

It has long been recognised that the rare earth elements, e.g. Nd, Er, and Yb, display fluorescent properties which make them suitable for use as fluorescent additives in optical fibre. Their fluorescent properties make them particularly suitable for use in the laser devices mentioned above. The operation of a fluorescent device clearly depends on absorption of the pump photons in order to raise ions (or other
25 fundamental particles) of dopant to an excited state for subsequent emission on a different transition. In a laser device, this emission is stimulated by the presence of a signal photon and, therefore, the operation of a laser device also depends on the interaction of radiation at signal wave length. It is an object of this invention to make efficient use of pump power launched into optical fibre. In the case of optical amplifiers this means achieving high gain for small launched pump powers whereas for optical oscillators it implies a low lasing threshold.

30 Fibre according to the invention has a fluorescent additive unevenly distributed over the cross section of the core and having a higher concentration of the additive at the centre of the core than at the core/cladding boundary. The highest concentrations of additive should ideally be located in those regions of the fibre where, during pumping, the highest intensity of pump radiation is to be expected. Lower or zero concentrations of the additive should be located where only low pump intensities are to be expected.

40 In most pumping schemes the highest intensity of the pump radiation will be located at the centre of the core and it is appropriate to provide the highest dopant concentration at the centre of the core with zero concentration at its periphery. Preferably the core comprises two zones, namely an inner zone surrounded by an outer zone wherein the inner zone contains the dopant and the outer zone contains substantially no dopant. Suitably the inner zone constitutes less than a quarter, e.g. 5 to 15 %, of the cross sectional area of
45 the core.

The fibre may be implemented in any glass system which is compatible with the fluorescent dopants. Thus, for example, the fibre may be implemented in conventional silicate, phosphate and fluoride systems, eg. fluorides of Zr, Ba, La, Al, Na and Hf or in silica systems, eg. SiO_2 with additives such as GeO_2 to adjust the refractive index in the core.

50 In a specific embodiment silica fibre has

- (a) a cladding formed of SiO_2 with P_2O_5 to reduce the melting point, and F to offset the increase in refractive index;
- (b) an outer core region formed of SiO_2 with GeO_2 to increase the refractive index and P_2O_5 to reduce the melting point; and
- 55 (c) an inner core region formed of SiO_2 with Al_2O_3 to increase the refractive index, P_2O_5 to decrease the melting point and prevent devitrification and a fluorescent dopant to interact with the pump radiation.

The dimensions of the fibre are preferably such that it is single mode at signal wave length. This implies that it may be able to support several, e.g. up to 4 or 5, modes at pump frequency. The fluorescent

dopants of major interest include the rare earth metals. Of these the most important are Er (which lases by the three level mechanism) and Nd (which lases by the 3 and four level mechanism)

One method of making optical fibre according to the invention utilises the modified chemical vapour deposition process usually identified as MCVD. MCVD is sometimes known as the inside deposition process because the glasses which eventually form the operative parts of the fibre are produced by converting the equivalent chlorides into the desired oxides which are deposited, layer by layer, on the inner surface of a substrate tube. Usually a total of 10 to 30 layers are deposited. As initially deposited the glass is porous but the porous material is immediately fused to give a solid layer upon which subsequent layers are deposited. When all the layers have been deposited the tube is collapsed to a rod which is drawn into fibre.

To make fibre according to the invention this procedure is followed for the cladding and the outer core. The precursor of the inner core is deposited but left in the porous state. Dopants, including the fluorescent additive, are introduced as solution into the porous layer. After solvent removal and conversion to oxides as necessary, the porous layer is consolidated and the tubular configuration is collapsed into a rod which is then drawn into fibre.

It will be appreciated that this, i.e. soaking a solution into a porous layer, is one of many known techniques of introducing dopants into optical fibre. It has been adapted, in accordance with the invention, to provide a small, doped centre region in a larger core. One difficulty inherent in MCVD is that there is a tendency to lose dopant by evaporation from the exposed inner surface. This is not acceptable since the invention requires a high concentration of dopant at the axis. The depleted zone can be removed, e.g. by etching, just before final collapse. Although there appears to be a risk that further losses could occur during the final stage of the collapse, this does not happen to any noticeable extent because:-

(1) The exposed surface is so small that the rate of loss is minimal.

(2) The final stage only takes a time which is too brief for noticeable loss to occur.

However we have most surprisingly discovered that, when aluminium is used to adjust the refractive index of the core, the losses of fluorescent dopant are not noticeable. The aluminium can be introduced at the same time as the fluorescent dopant, e.g. as $\text{Al}(\text{NO}_3)_3$ in alcoholic solution. During heating the $\text{Al}(\text{NO}_3)_3$ is converted to Al_2O_3 .

The fibre according to the invention can be used to make conventional fibre devices which include a pump for providing excitation radiation for the fluorescent additive.

The invention will now be described by way of example with reference to the accompanying drawing which is a cross section through a fibre according to the invention;

The drawing shows a fibre according to the invention prepared by the MCVD process. This fibre has a residual layer 10 which is the residue of the substrate tube used in the MCVD process. The layer 10 has no optical function. The fibre also has a conventional cladding 11, a core which is generally indicated by the numeral 14, having an (undoped) outer region 12 an inner region 13 which contains a fluorescent dopant, e.g. Er, at a concentration of .001 - 10.0 wt % Er.

Fibre as described above was prepared by a substantially conventional MCVD process in which a substrate tube was rotated in a glass blowing lathe while a reactant gas was passed through its bore. In the course of the preparation three different reactant mixtures, to be specified below, were used.

A short segment of tube, about 2cm long, was heated to reaction temperature by a travelling flame. In this segment chlorides were converted into oxides which deposited as a porous ring downstream of the flame. As the flame traversed, in the case of cladding and outer core, the deposit was fused to form a thin layer on the inner surface of the substrate tube. In the case of inner core, a lower temperature was used so that the deposit did not fuse whereby it remained porous.

The reaction mixture used to form the cladding precursor was obtained by bubbling:-

700ml/min of O_2 through SiCl_4 ,

90ml/min of O_2 through POCl_3 .

The mixture of these two gas streams was diluted with 1.5 litre/min O_2 and 1.0 litre/min He. In addition, 6 ml/min of CCl_2F_2 were included in the mixture. The maximum temperature in the hot zone was 1600°C and the flame travelled at 18cm/min.

Five cladding layers were thus deposited on a substrate tube of 10mm inner diameter. These fused together to form a cladding layer of SiO_2 doped with P_2O_5 and fluorine.

(The P_2O_5 , which is derived from the POCl_3 , is incorporated to reduce the melting point of the SiO_2 which makes the fusion easier. The P_2O_5 slightly increases the refractive index of the silica but the fluorine slightly reduces the refractive index. By balancing the two concentrations the refractive index of the five cladding layers is substantially equal to that of pure silica. Thus the POCl_3 and CCl_2F_2 are processing aids which have little or no effect on the performance of the final product which, therefore, consists essentially of

SiO₂).

Eight layers to form the outer core were deposited next. The reaction mixture used for each layer was obtained by bubbling:-

200 ml/min at O₂ through SiCl₄

5 200 ml/min of O₂ through GeCl₄

10 ml/min of O₂ through POCl₃.

The mixture of these three gas streams was diluted with 1.5 litres/min of O₂. These eight layers were fused together at 1500°C and the flame travelled at 16 cm/min. This formed the outer core region which consisted essentially of SiO₂ doped with GeO₂ to increase the refractive index and P₂O₅ to facilitate processing by lowering the melting point of the glass.

10 The precursor at the inner core was deposited in two porous layers. The reaction mixture was obtained by bubbling:-

200 ml/min of O₂ through SiCl₄

10 ml/min of O₂ through POCl₃

15 and diluting with 1.5 litres/min of O₂. The torch traverse rate was 17 cm/min and the maximum temperature was at 1000°C (which is too low to fuse the deposit).

(Note. In all bubbling operations the liquid was at 25°C.) At this point the tube was removed from the lathe and dopants were introduced into the porous layers by immersion for 1 hour in an ethanolic solution of 1M Al(NO₃)₃

20 0.08M ErCl₃.

After soaking, the tube was drained, blown dry with N₂ for one hour, and returned to the lathe where it was heated at about 800°C - 1000°C for a few minutes. This completed solvent evaporation. The temperature was raised to about 1900°C for collapse to a rod. This also ensured conversion of Al(NO₃)₃ to Al₂O₃ and ErCl₃ to Er₂O₃. The tube was flushed with O₂/He mixture during all of these stages (about 10 % (volume) of Cl₂ could be introduced into the O₂/He mix if a very dry product were required.)

25 The resulting preform had a core about 2mm diameter. Analysis (using dispersive X-ray techniques) confirmed that Al and Er³⁺ were confined to the central region. The reason for choosing a large core will be briefly explained.

30 The ultimate objective is a fibre having the dopant, Er³⁺, contained in a very small inner core, e.g. with a diameter of 1 to 3µm. It was decided to achieve this by means of a fat outer core (8 layers), a thin inner core (2 layers) and a high overall draw ratio, i.e. length extension of about 1:10⁵.

The fatness of the preform made it difficult to handle and it was drawn in two stages. First the external diameter was reduced from 7.0mm to 3.2mm, i.e. an axial draw of 1:4.8. The drawn rod was sleeved with a silica tube and then drawn 1: 2.5x10⁴ to give the product fibre.

35 (There is a well known problem that dopants are lost during collapse from the inner layers of the preform. This results in a thin axial depletion zone. In the process above described Al₂O₃ was present and in the presence of this compound no loss of Er³⁺ occurred.) The product fibre had the following measurements.

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Cladding (11)OD 7 μ mID 4 μ m

RI matched to silica

Core Outer Region 12OD 4 μ mID 1.5 μ mEr³⁺ NONECore Inner Region 13Diameter 1.5 μ mEr³⁺ 1 wt %General PropertiesOD 125 μ mLP₁₁ Cut Off 790 nm

RI step 0.01

"RI step" denotes the difference between the RI of the core and the RI of the cladding.

A possible theory of the operation of this fibre will now be briefly indicated.

The considerations set out above are particularly pertinent to dopants which lase as a three level system. The three levels are:-

- (a) The ground state,
- (b) the pump level,
- (c) upper laser level, (also known as the metastable level).

The absorption of a pump photon by a ground state ion transfers that ion to the upper pump level from where it decays non-radiatively to the upper laser level. That ion can then return to the ground state via the lasing transition, i.e. gives out a signal photon. In order to achieve the population inversion essential for laser operation it is necessary to pump more than half the dopant ions from the ground state to the upper laser level. Thus it is important to note that, at a particular point in space, if fewer than half the ions have been pumped to the upper laser level then the signal beam will be attenuated at that point.

It is therefore extremely desirable to preferentially locate the fluorescence additive where the pump intensity is highest, i.e. on the axis and to prevent there being any dopant ions in the regions where the pump intensity is lower.

The signal beam, which being single mode also has its maximum intensity on the axis, overlaps well with the excited dopant ions and thus effectively depopulates the upper laser level.

In order to illustrate the benefit of the invention comparative measurements were made on two very similar fibres both of which used Er³⁺ ions as the fluorescent species. The fibre, identified as "A", had the Er³⁺ ions located in a centre core Region 13 as shown in Figure 1. The comparative fibre, identified as "X", had the more standard Er³⁺ distribution, i.e. uniformly distributed over the whole of the core. Details of both fibres are given in Table 1.

Diameters (μm)	A	X
Total	125	125
To Cladding (11)	6.0	6.0
To Core (12)	3.5	3.5
Inner Region (13)	1.0	NONE
RI Step	0.0100 \pm 0.005	0.0095 \pm 0.005
LP ₁₁ Mode cut off (nm)	790	790

In the case of fibre A the dopant was contained only in the inner region 13. Based on this region alone the concentration of Er^{3+} was 0.45% wt or 0.037% wt based on the total core 14. For fibre X the concentration of Er^{3+} was 0.05% wt based on the total core 14.

The performances of the two fibres were compared by measuring the "transparency power" of each.

To measure the transparency power a short length of fibre is used so that pump power does not change significantly along the length. The test comprises launching the signal at wave length 1.54 μm and pump at wave length 528.7nm into the opposite ends of the fibre. The input and output powers of the signal are measured for several values of pump power. There exists a specific pump power at which the signal is neither amplified or attenuated and this power is known as the "transparency power". This name is considered appropriate because, at this pump power, the fibre simulates a perfectly transparent window. At higher pump powers than the transparency power, the fibre amplifies the signal beam whereas at lower pump powers the fibre attenuates the signal beam. The transparency power is a direct measure of the performance of the invention and the lower the transparency power the better the performance. The transparency powers of the two fibres was

Fibre A	0.8mW
Fibre X	1.4mW
Ratio	1 : 1.75

Thus the fibre according to the invention gave gain at much lower pump power than the comparative fibre.

Claims

1. An optical fibre, suitable for forming fluorescent devices, which contains a fluorescent dopant in its core, characterised in that the concentration of the dopant is greater on the core axis than at the interface between the core and the cladding.
2. A fibre according to Claim 1 wherein the core comprises an inner region and an outer region surrounding the inner region wherein substantially all of the dopant is contained in the inner region.
3. A fibre according to claim 2, wherein the inner region constitutes not more than a quarter of the total cross sectional area of the core.
4. A fibre according to claim 3, wherein the inner region constitutes 5% to 15% of the cross sectional area of the core.
5. A fibre according to any one of claims 2 to 4, wherein both core regions contain SiO_2 and the mole ratio of Si to dopant in the inner core region is between $1:10^{-4}$ and $1:10$.
6. A fibre according to any one of claims 2-5, wherein the dopant is substantially uniformly distributed in the inner region of the core.
7. A fibre according to any one of the preceding claims which is monomode at signal wave length.
8. A fibre according to any one of the preceding claims wherein the dopant is capable of lasing transition.
9. A fibre according to Claim 8, wherein the dopant is a three level lasing element.

10. A fibre according to any one of the preceding claims, wherein the dopant is a rare earth element.
11. A fibre according to claim 10, wherein the dopant is selected from Er, Nd, Pr, Ho, Yb and Tm.
- 5 12. A fibre according to claim 11, wherein the dopant is Er^{3+} .
13. An optical fibre which comprises
 - (a) a cladding region formed of a first glass composition having a first refractive index;
 - (b) an outer core region surrounded by said cladding region and formed of a second glass
10 composition having a second refractive index said second refractive index being higher than said first refractive index;
 - (c) an inner core region surrounded by said outer core region and formed of a third glass composition having a refractive index substantially equal to said second refractive index wherein said
15 third glass composition contains a dopant which provides an element selected from Er, Nd, Pr, Ho, Yb and Tm in a form capable of undergoing lasing transitions wherein the concentration of said
dopant is such as to provide about 1 to 10% by weight of said element based on the total third glass composition.
14. An optical fibre according to claim 13, wherein the concentration of the dopant is 0.1 to 10% by weight.
15. An optical fibre according to any one of the preceding claims, wherein the cladding region consists essentially of SiO_2 , the outer core region consists essentially of SiO_2 and GeO_2 and the inner core region consists essentially of SiO_2 , GeO_2 and the lasing dopant.

25 Patentansprüche

1. Optische Faser, die geeignet ist zum Bilden fluoreszierender Vorrichtungen, welche eine fluoreszieren-
de Dotierung in ihrem Kern enthält, dadurch gekennzeichnet, daß die Konzentration der Dotierung auf
der Kernachse größer ist als an der Grenzfläche zwischen dem Kern und der Plattierung.
2. Faser nach Anspruch 1, wobei der Kern einen inneren Bereich und einen den inneren Bereich
umgebenden äußeren Bereich aufweist, wobei im wesentlichen die gesamte Dotierung in dem inneren
Bereich enthalten ist.
3. Faser nach Anspruch 2, wobei der innere Bereich nicht mehr als ein Viertel der gesamten Querschnitts-
fläche des Kerns bildet.
4. Faser nach Anspruch 3, wobei der innere Bereich 5 % bis 15 % der Querschnittsfläche des Kerns
darstellt.
5. Faser nach einem der Ansprüche 2 bis 4, wobei beide Kernbereiche SiO_2 enthalten und das
Molverhältnis von Si zur Dotierung in dem inneren Kernbereich zwischen $1:10^{-4}$ und $1:10$ liegt.
6. Faser nach einem der Ansprüche 2 bis 5, wobei die Dotierung im wesentlichen gleichförmig in dem
inneren Bereich des Kerns verteilt ist.
7. Faser nach einem der vorhergehenden Ansprüche, die bei einer Signalwellenlänge eine Monomodentfa-
ser ist.
8. Faser nach einem der vorhergehenden Ansprüche, wobei die Dotierung zu einem Laserübergang in der
Lage ist.
9. Faser nach Anspruch 8, wobei die Dotierung ein 3-Niveau-Laserelement ist.
10. Faser nach einem der vorhergehenden Ansprüche, wobei die Dotierung ein Element der Seltenen
Erden ist.
11. Faser nach Anspruch 10, wobei die Dotierung aus Er, Nd, Pr, Ho, Yb und Tm ausgewählt ist.

12. Faser nach Anspruch 11, wobei die Dotierung Er^{3+} ist.
13. Optische Faser, welche aufweist:
- (a) einen Plattierungsbereich, der aus einer ersten Glaszusammensetzung mit einem ersten Brechungsindex gebildet wird.
 - (b) einen durch den Plattierungsbereich umgebenen äußeren Kernbereich, der aus einer zweiten Glaszusammensetzung gebildet ist mit einem zweiten Brechungsindex, wobei der zweite Brechungsindex höher ist als der erste Brechungsindex;
 - (c) einen durch den äußeren Kernbereich umgebenen inneren Kernbereich, der aus einer dritten Glaszusammensetzung gebildet ist mit einem Brechungsindex, der im wesentlichen gleich dem zweiten Brechungsindex ist, wobei die dritte Glaszusammensetzung eine Dotierung enthält, die ein Element bereitstellt, welches aus Er, Nd, Pr, Ho, Yb und Tm in einer Form ausgewählt wird, die in der Lage ist, sich Laserübergängen zu unterziehen, wobei die Konzentration der Dotierung derart ist, daß 0,001 bis 10 Gewichtsprozent Element bezogen auf die gesamte Glaszusammensetzung bereitgestellt ist.
14. Optische Faser nach Anspruch 13, wobei die Konzentration der Dotierung 0,1 bis 10 Gewichtsprozent ist.
15. Optische Faser nach einem der vorhergehenden Ansprüche, wobei der Plattierungsbereich im wesentlichen aus SiO_2 besteht, der äußere Kernbereich im wesentlichen aus SiO_2 und GeO_2 besteht und der innere Kernbereich im wesentlichen aus SiO_2 , GeO_2 und der Laserdotierung besteht.

Revendications

1. Une fibre optique, apte à former des dispositifs fluorescents, qui contient dans son noyau un dopant fluorescent, caractérisée en ce que la concentration de dopant est plus grande sur l'axe du noyau qu'à l'interface entre le noyau et la gaine.
2. Une fibre selon la revendication 1 dans laquelle le noyau comprend une zone intérieure et une zone extérieure, entourant la zone intérieure, dans laquelle sensiblement tout le dopant est contenu dans la zone intérieure.
3. Une fibre selon la revendication 2, dans laquelle la zone intérieure ne constitue pas plus d'un quart de la surface totale d'une coupe transversale du noyau.
4. Une fibre selon la revendication 3, dans laquelle la zone intérieure constitue de 5 % à 15 % de la surface d'une coupe transversale du noyau.
5. Une fibre selon l'une quelconque des revendications 2 à 4, dans laquelle les deux zones de noyau contiennent du SiO_2 et le rapport molaire entre Si et le dopant dans la zone intérieure de noyau est compris entre $1:10^{-4}$ et $1:10$.
6. Une fibre selon l'une quelconque des revendications 2 à 5, dans laquelle le dopant est réparti de façon sensiblement uniforme dans la zone intérieure du noyau.
7. Une fibre selon l'une quelconque des revendications précédentes qui est monomode à la longueur d'onde de signal.
8. Une fibre selon l'une quelconque des revendications précédentes dans laquelle le dopant est susceptible d'une transition à effet laser.
9. Une fibre selon la revendication 8, dans laquelle le dopant est un élément à effet laser à trois niveaux.
10. Une fibre selon l'une quelconque des revendications précédentes, dans laquelle le dopant est un élément des terres rares.
11. Une fibre selon la revendication 10, dans laquelle le dopant est choisi parmi Er, Nd, Pr, Ho, Yb et Tm.

12. Une fibre selon la revendication 11, dans laquelle le dopant est Er^{3+} .
13. Une fibre optique qui comprend :
 - (a) une zone de gaine formée d'une première composition de verre à premier indice de réfraction;
 - (b) une zone extérieure de noyau entourée par ladite zone de gaine et formée d'une deuxième composition de verre à deuxième indice de réfraction, ledit deuxième indice de réfraction étant supérieur audit premier indice de réfraction;
 - (c) une zone intérieure de noyau entourée par ladite zone extérieure de noyau et formée d'une troisième composition de verre à indice de réfraction sensiblement égal audit deuxième indice de réfraction, dans laquelle ladite troisième composition de verre contient un dopant qui inclut un élément choisi parmi Er, Nd, Pr, Ho, Yb et Tm sous une forme susceptible d'être soumise à des transitions d'effet laser et dans laquelle la concentration dudit dopant est apte à constituer 0,001 à 10 % en poids dudit élément, sur la base du poids total de la troisième composition de verre.
14. Une fibre optique selon la revendication 13, dans laquelle la concentration du dopant est comprise entre 0,1 et 10 % en poids.
15. Une fibre optique selon l'une quelconque des revendications précédentes, dans laquelle la zone de gaine consiste essentiellement en SiO_2 , la zone extérieure de noyau consiste essentiellement en SiO_2 et GeO_2 et la zone intérieure de noyau consiste essentiellement en SiO_2 , GeO_2 et le dopant à effet laser.

